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**ATMOSPHERIC DENSITY ABOVE 158 km INFERRED FROM
MAGNETRON AND DRAG DATA FROM THE
SATELLITE OV1-15(1968-059A)**

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FOREWORD

This report is published by The Aerospace Corporation, El Segundo, California, under Air Force Contract F04701-69-C-0066.

The authors would like to thank Dr. Robert A. Becker, who was instrumental in the development of OV1-15, for his continuing support and encouragement. They are grateful also to Mr. E. Borson for many helpful discussions and for the use of his high vacuum system; Mr. R. Marcoe for technical assistance; Messrs. K. Hubbard and W. Downs for computer support in the drag analysis; and Dr. S. Creekmore who, with the assistance of Mrs. M. Brennan, analyzed the satellite orientation data.

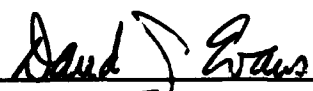
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Approved


G. A. Paulikas, Director
Space Physics Laboratory

Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.


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Project Officer

ABSTRACT

A cold-cathode magnetron pressure gauge and a C-band radar beacon were part of the complement of experiments aboard the polar-orbiting atmospheric research satellite OV1-15 (1968-059A). Over the period 13-15 July 1968, when the perigee of the satellite was near the equator at about local noon, the atmospheric density profiles were repeatedly measured down to 158 km. The profiles agreed in the northern and southern hemispheres below 200 km, but above 200 km the northern profile was greater than the southern, in approximate agreement with the Jacchia model that includes a symmetric density bulge at the subsolar latitude at 1400 hr local time.

During a moderate magnetic disturbance, the atmospheric density at latitudes below about 40° increased with an amplitude and lag that are adequately described by the Jacchia model, except that the duration of the density enhancement was several hours longer than the duration of the geomagnetic disturbance. At latitudes above 40° (which were available to us only in the southern hemisphere) the density enhancement decreased markedly with increasing latitude, an occurrence not predicted by the model.

The drag-determined density near perigee was the same, within the estimated errors, as that determined from the gauge measurement, in contrast to the factor-of-two discrepancy found in a similar comparison of data from the satellite Explorer 17.

CONTENTS

FOREWORD	ii
ABSTRACT	iii
I. INTRODUCTION	1
II. PAYLOAD, SPACECRAFT, AND ORBIT INFORMATION	3
III. MAGNETRON GAUGE MEASUREMENT	9
A. Gauge	9
B. Calibration	9
C. Flight Data	12
D. Density Determination	15
E. The O vs O ₂ Problem	15
F. Results	16
IV. DRAG MEASUREMENT	23
V. CONCLUSIONS	25
REFERENCES	27

TABLE

I. The Complement of Instruments on OV1-15	4
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FIGURES

1.	The OV1-15 spacecraft	5
2.	The orbit of OV1-15 with perigee at the equator	7
3.	The altitude and latitude of perigee over the orbital lifetime of OV1-15	8
4.	Schematic of the cold-cathode magnetron pressure gauge	10
5.	Laboratory calibration of the current output of the pressure gauge vs static pressure of N_2	11
6.	Typical portion of the telemetered signal from the pressure gauge's logarithmic electrometer, taken on rev 25 at 378 km altitude	13
7.	Pressure in ram and wake vs altitude, revs 25 and 109	14
8.	Density vs altitude inferred from pressure measurements during revs 21, 25, and 29 (13 July 1968)	17
9.	Average density for seven revs over the period 13-15 July 1968, at 1130 hr local time	19
10.	Density at several altitudes vs time	21

I. INTRODUCTION

The atmospheric research satellite OV1-15 (1968-059A) was developed for three purposes: (1) to gather synoptic data on atmospheric density and composition at low satellite altitudes, where previously data have come from probes [e.g., Pelz and Newton, 1969; von Zahn, 1967] and satellite drag [e.g., King-Hele and Quinn, 1966; Jacobs, 1967]; (2) to test the discrepancy between gauge and drag measurements of density found by Explorer 17 [Newton, et al., 1965]; and (3) to attempt to determine in situ the mechanism responsible for the increase in the density observed during geomagnetic storms [Jacchia, 1961]. This paper reports the first results of the cold-cathode gauge measurement of density during times of relatively moderate solar and magnetic activity and compares the perigee density with that determined from drag.

The experiments on OV1-15 were performed by the Space Physics Laboratory of The Aerospace Corporation and by Air Force Cambridge Research Laboratories; the satellite and range support were supplied through the U. S. Air Force Office of Aerospace Research.

II. PAYLOAD, SPACECRAFT, AND ORBIT INFORMATION

The complement of experiments on OV1-15 is listed in Table I. The heating source experiments were those designed to measure major sources of energy deposition in the atmosphere, for the purpose of attempting to identify the dominant source that causes the magnetic-storm-related density increase.

The spacecraft, produced by General Dynamics/Convair, is illustrated in Fig. 1. The location of the cold-cathode gauge described in this paper is indicated. The satellite weighed 475 lb, generated 30 to 50 W-hr/orbit, and was initially spun at 9 rpm. The spin axis was nominally perpendicular to the orbit plane; thus the density and composition instruments looked alternately into the ram and wake. Aerodynamic pressure at perigee caused drift of the spin axis direction, so every few days the satellite was reoriented with the onboard electromagnet (which coupled to the earth's magnetic field at appropriate locations) in order to bring the spin axis back to the desired alignment. Any induced wobble was then damped with a passive system. The orientation of the spacecraft was determined by two different techniques: (1) the ionospheric ram-current method used previously on Gemini X and XII [Sagalyn and Smiddy, 1969], and (2) a simultaneous measurement of \vec{B}_{earth} and the sun's direction, by use of an onboard three-axis magnetometer and a set of directional solar cells. The second system was used in the analysis in this paper, and it yielded knowledge of the orientation angles to an accuracy of ± 5 deg. Every fourth rev, the outputs of the experiments were tape recorded for a 24-min period centered around perigee, and then the tape recorder was read out about once a day. The timing of the automatic programmer that initiated the data acquisition was periodically updated by ground command. A special reserve battery was included in the payload to allow an increased duty cycle during selected periods of magnetic activity.

Table I. The Complement of Instruments on OV1-15

DENSITY AND COMPOSITION EXPERIMENTS

INSTRUMENT	MEASUREMENT	LABORATORY
ION GAUGES (3)	PRESSURE	A & CRL
ACCELEROMETER	DRAG	CRL
BEACON TRACKING	AVERAGE DRAG	A & CRL
MASS SPECTROMETERS (3)	NEUTRAL AND ION COMPOSITION	A & CRL
MICROPHONE GAUGE	DENSITY	LPARL

HEATING SOURCE EXPERIMENTS

SOLAR X-RAY SPECTROMETER	1-13 Å, $\Delta\lambda \sim 2\text{Å}$	A
SOLAR UV PHOTOMETERS	300-1700 Å IN 6 BANDS	A
ENERGETIC PARTICLE DETECTORS	PRECIPITATING PROTONS AND ELECTRONS 1-100 keV	A
ION TRAPS (2)	DENSITY AND TEMPERATURE OF IONOSPHERE	A & CRL

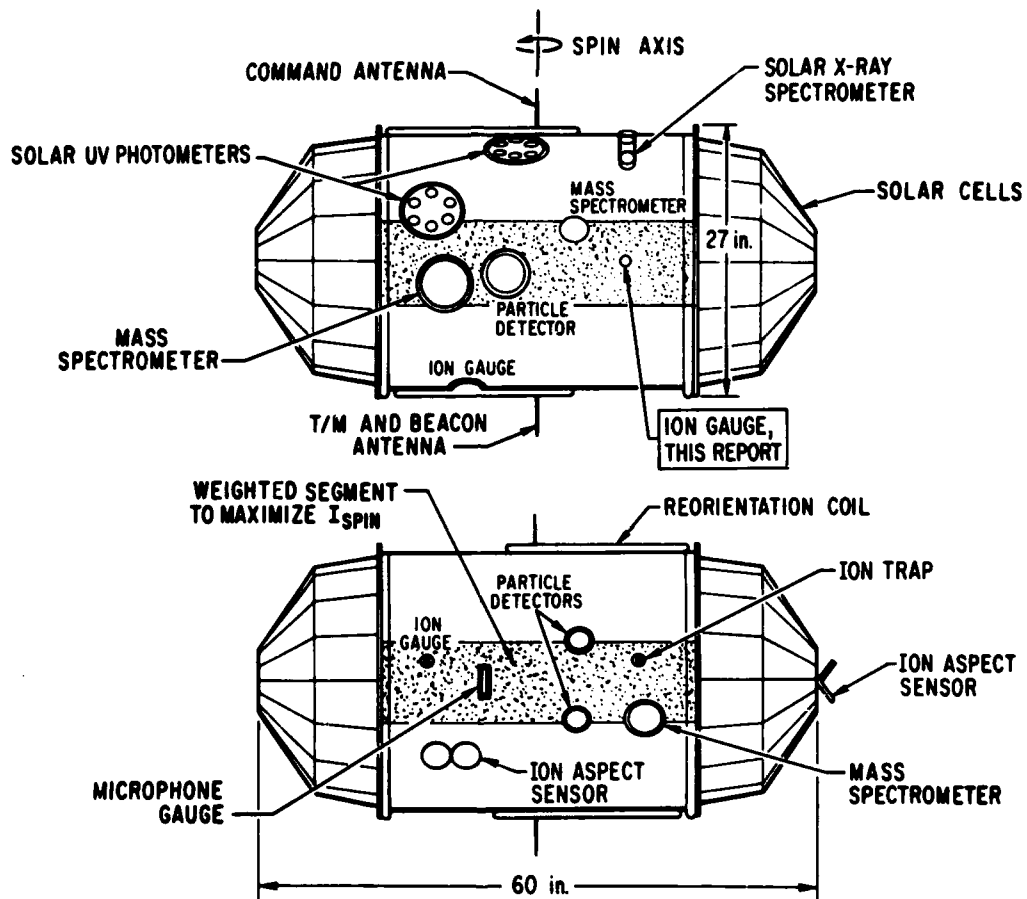


Figure 1. The OV1-15 spacecraft

OV1-15 was boosted from Vandenberg Air Force Base into a polar orbit by an Atlas missile on 11 July 1968 and reentered 6 November 1968. The orbit shown in Fig. 2 depicts perigee at the equator, although for the several revs reported in this paper the perigee latitude moved from 12°S to 6°S. The elliptical orbit was chosen to give a 4-mo orbital lifetime with the desired low-altitude perigee. (The choice was fortunate in that the only major magnetic storm occurred the week before reentry.) The 24-min record period translated into a 100° latitudinal arc during which time (for the early revs reported in this paper) the satellite was below 400 km and passed from the north, through perigee, to the south. The perigee position precessed at about 3.5° per day in a clockwise direction in the view shown in Fig. 2. Over the satellite lifetime the position of perigee swept out all latitudes while the perigee altitude remained within ± 13 km of 160 km up until the last 2 weeks before reentry (Fig. 3). The local time was essentially constant over each rev, but moved seasonally from an initial value of 1130 hr on the daytime side of the orbit, to a dawn-dusk meridian 3 mo later.

The ephemeris of OV1-15 was calculated from the orbital elements supplied by the U. S. Air Force Air Defense Command and was accurate to within 1 km in altitude and 0.1° in latitude. For orbital drag analysis, however, the C-band beacon data were used and yielded perigee-altitude and latitude to an accuracy of 0.1 km and 0.3 sec of arc, respectively.

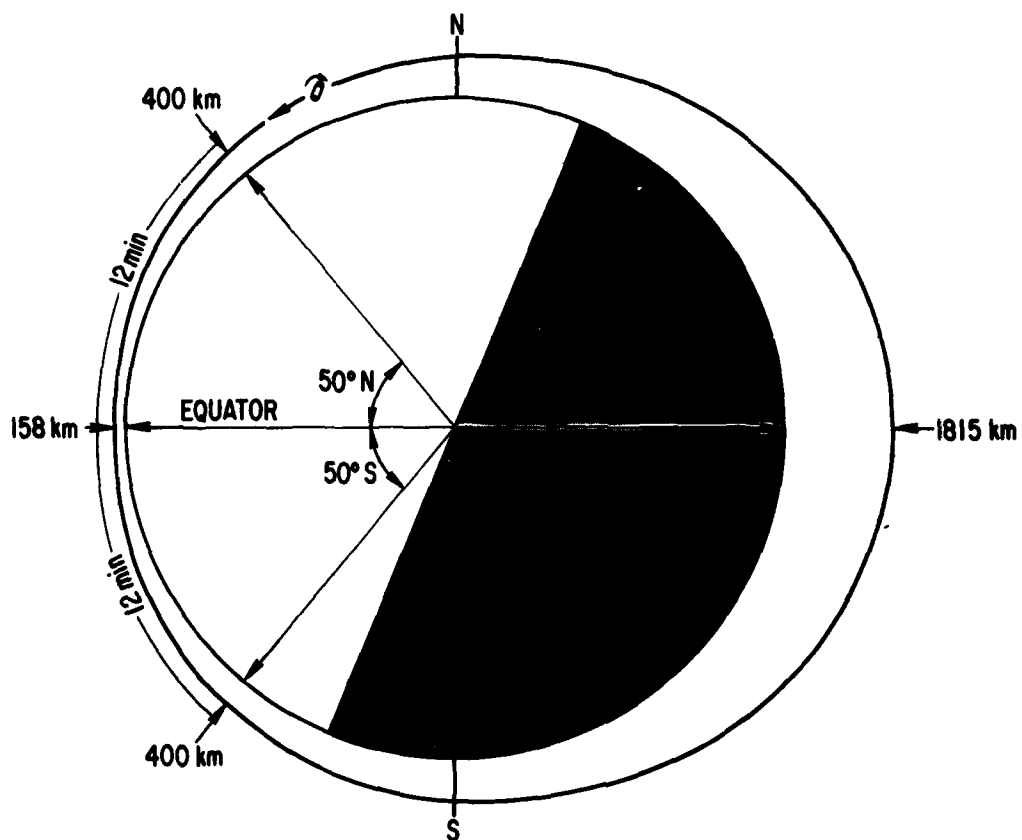


Figure 2. The orbit of OV1-15 with perigee at the equator

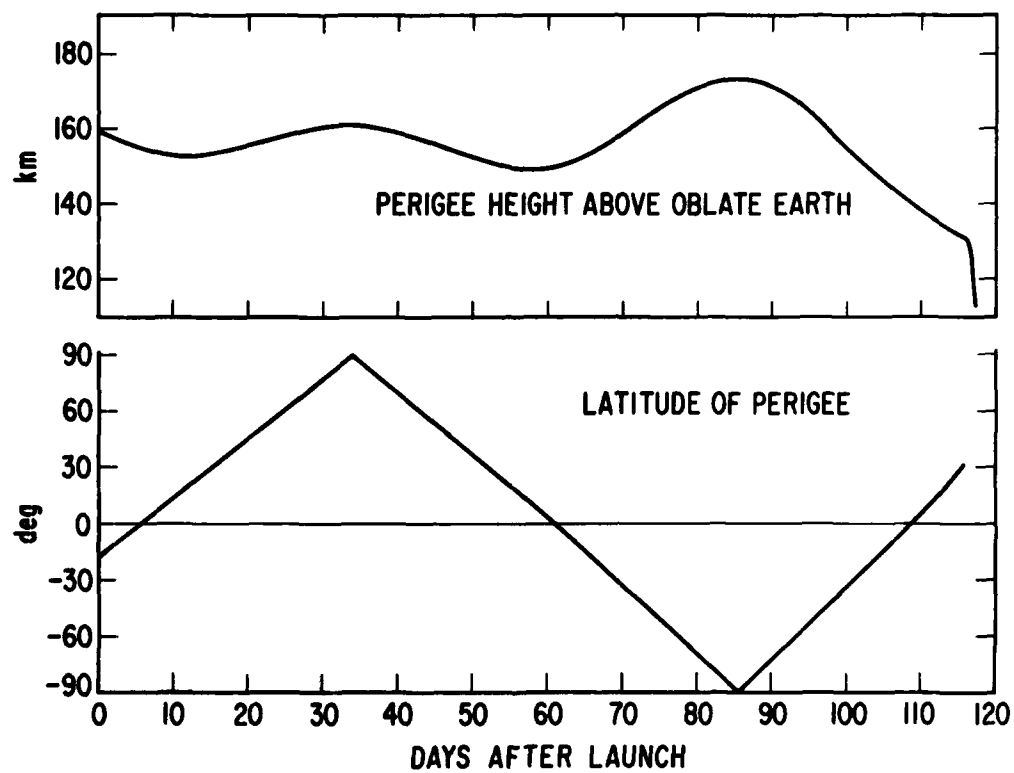


Figure 3. The altitude and latitude of perigee over the orbital lifetime of OV1-15

III. MAGNETRON GAUGE MEASUREMENT

A. GAUGE

A cold-cathode magnetron pressure gauge of rugged design, built by the National Research Corporation (NRC), was located on the spin equator of OV1-15. The gauge was maintained at vacuum through launch and orbital injection, and then the orifice cover was squib-released after the completion of several revs. Figure 4 presents a schematic of the gauge. The anode cylinder was spaced away from the gauge housing on three synthetic sapphire balls. The forward pole pieces served in addition as ion traps and photon baffles, providing a neutral gas conductance which resulted in a ratio of tumbling frequency to transpiration frequency of 5×10^{-2} . The log electrometer had two overlapping ranges, providing output of from 0 to 5 V for pressures ranging from 10^{-11} to 5×10^{-8} torr and from 10^{-8} to 1.5×10^{-5} torr. The telemetry error inherent in the PCM system, because of the least-significant-bit threshold, was $\pm 6\%$. The experiment weighed 4.25 lb, drew 1.5 W of power, and used 20 prime data words a second, 10 each of electrometer signal and electrometer range status.

B. CALIBRATION

Calibration of the gauge was performed in nitrogen from 10^{-10} to 10^{-3} torr as shown in Fig. 5. There was a pronounced change in mode around 4×10^{-10} torr, which was accompanied by marked instability. Above 10^{-8} torr the gauge response was stable and reproducible. Our calibration of the gauge, with a calibrated Bayard-Alpert gauge as a secondary standard, fell within 10% of the calibration data provided by NRC. The absolute accuracy of the calibration was estimated to be $\pm 12\%$ above 10^{-8} torr. The gauge showed a typical break in response at 10^{-8} torr, and at lower pressures, down to the region of instability in the 10^{-10} torr range, the accuracy of calibration was $\pm 25\%$.

In reducing the flight data, we have assumed a gauge response in molecular oxygen equal to that in nitrogen and a response in atomic oxygen equal to

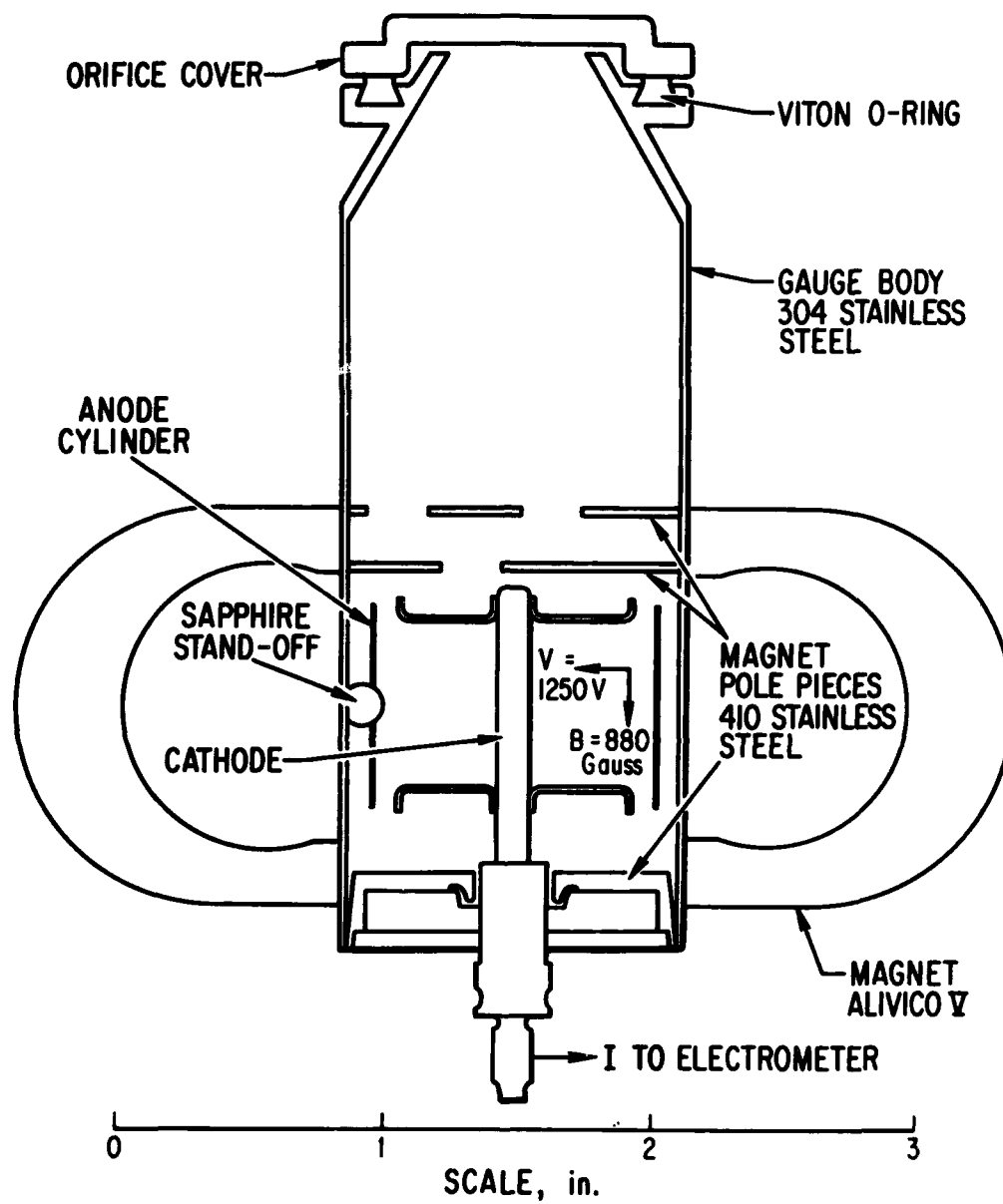


Figure 4. Schematic of the cold-cathode magnetron pressure gauge

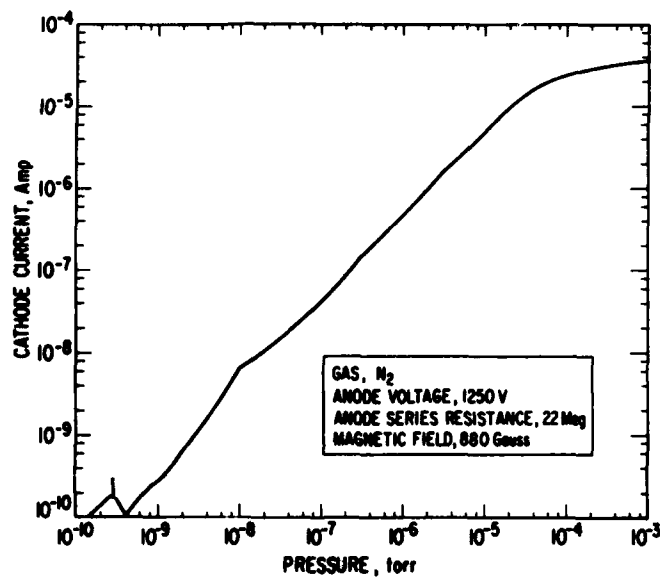


Figure 5. Laboratory calibration of the current output of the pressure gauge vs static pressure of N_2

0.63 of that in molecular oxygen, in accordance with the ionization efficiency data summarized by von Engel [1965] and the electron impact ionization cross section data summarized by Kieffer and Dunn [1966] and Fite and Brackmann [1959].

C. FLIGHT DATA

Figure 6 shows a typical portion of the telemetered signal from the gauge's electrometer, taken on rev 25 when the satellite was at 378 km. With the electrometer in its most sensitive range, the voltage corresponding to an internal pressure resulting from gauge outgassing was measured when the gauge orifice was directed into the satellite wake. As the gauge swung out of the wake, the pressure rose sharply; the electrometer switched to its less sensitive range; and the signal reached a maximum in the ram position. The pressure then decreased, with the overall curve showing an asymmetry due to adsorption and outgassing. The satellite spin period was 6.5 sec, resulting in 65 data points being acquired from peak to peak.

Figure 7 shows a plot of the gauge nitrogen-equivalent pressure in ram and in wake versus altitude for revs 25 and 109. Below 350 km, the wake pressure (outgassing) was always less than 10% of the pressure measured in ram, and at perigee it amounted to a fraction of 1%. The ram pressure profiles were different before and after perigee, a phenomenon discussed in a subsequent section, but the profiles were the same for revs 25 and 109. The wake pressure profiles differed not only before and after perigee but from rev 25 to 109. The former effect was due presumably to greater outgassing after the gauge had been exposed to the relatively high pressures near perigee. The decrease in wake pressure between revs 25 and 109 suggests that the outgassing rate decreased with time.

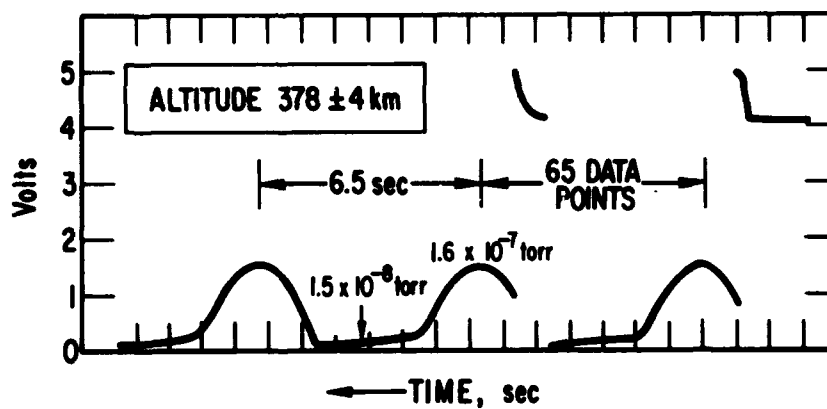


Figure 6. Typical portion of the telemetered signal from the pressure gauge's logarithmic electrometer, taken on rev 25 at 378 km altitude

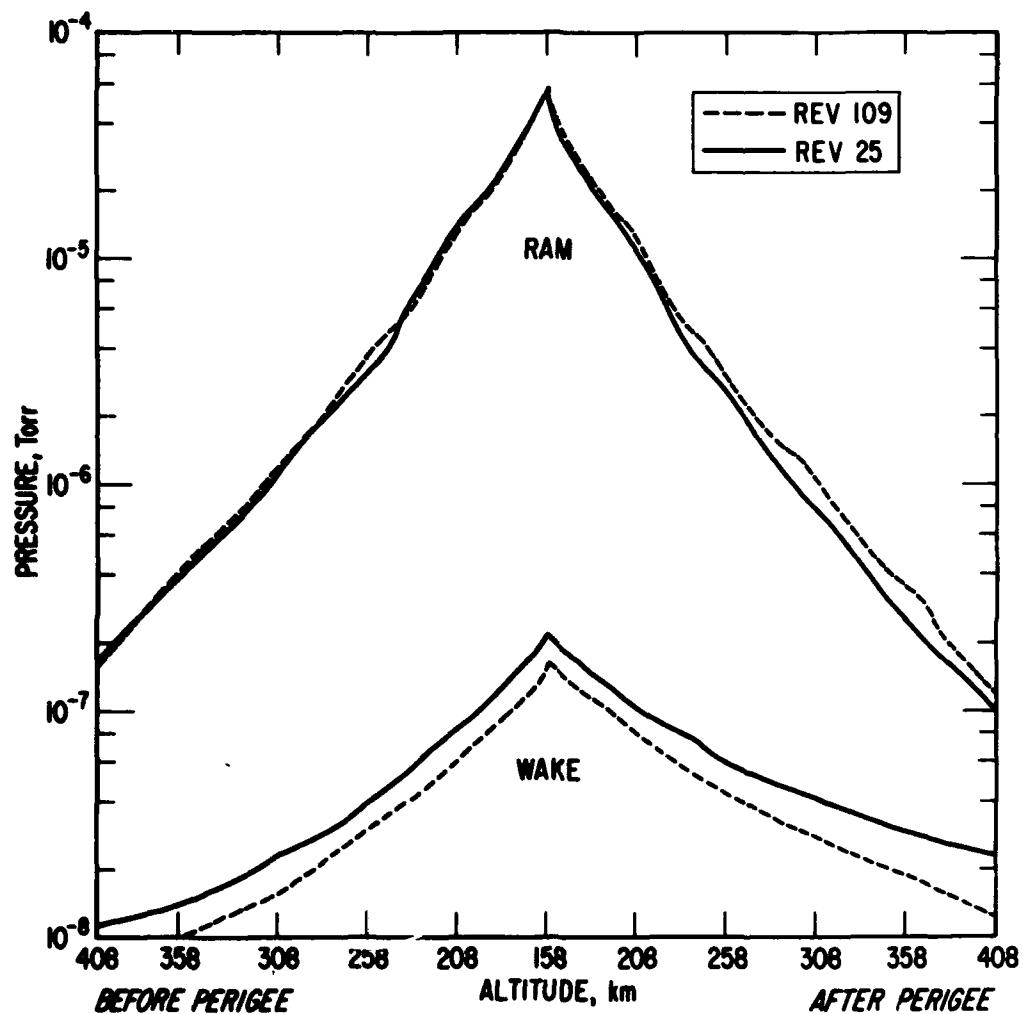


Figure 7. Pressure in ram and wake vs altitude, revs 25 and 109

D. DENSITY DETERMINATION

Atmospheric density was obtained from the gauge output by use of the equation [Newton, et al., 1965; Havens, et al., 1952]:

$$\rho = \frac{P(0^\circ) - P(180^\circ)}{\sqrt{\pi} v_i V_1}$$

where ρ is the density in gm/cm³, $P(0^\circ)$ and $P(180^\circ)$ are the indicated gauge pressures in dynes/cm² in ram and wake, respectively; V_1 is the component of the satellite velocity in cm/sec, perpendicular to the gauge opening in ram; and $v_i = \sqrt{\frac{2 kT}{M}}$ where T is the absolute temperature of the gauge in °K and M is the mean particle weight inside the gauge, in grams.

The gauge temperature ($\sim 282^\circ\text{K}$) was obtained from a thermocouple strapped to the body of the gauge in the region of the discharge. In the ram position, the normal to the gauge orifice was measured to be within $\pm 5^\circ$ of the satellite's velocity vector, as determined from an analysis of the tracking and orientation data. The values of M were taken from the 1965 CIRA-5 (1200 hr) model atmosphere, and were adjusted to reflect a total recombination of atomic oxygen to form molecular oxygen within the gauge. The value of the density is relatively insensitive to the exact model or time of day selected because, in computing ρ , M enters in a square root. For example, an inappropriate choice of model number or time of day contributes no more than a $\pm 2\%$ error in the result.

E. THE O VERSUS O₂ PROBLEM

The extent to which recombination of atomic oxygen to form molecular oxygen took place inside of the gauge is not known and must be treated as a major uncertainty in the data analysis. In computing the atmospheric density, we have assumed total recombination and a gauge response appropriate for molecular oxygen (equal to that in N₂). In a pure oxygen atmosphere, the

ratio of the densities one would infer assuming no recombination $\rho(O)$ and total recombination $\rho(O_2)$ is given by

$$\frac{\rho(O)}{\rho(O_2)} = \frac{1}{K\sqrt{2}}$$

where

$$K = \frac{S(O)}{S(O_2)} .$$

$S(O)$ and $S(O_2)$ are the responses of the gauge in amps per torr to atomic and molecular oxygen, respectively.

The response of the gauge has been measured experimentally in helium and nitrogen, and the ratio of the gauge response in helium to that in nitrogen was 0.15 at pressures where the gauge response was stable. According to the ionization-efficiency data summarized by von Engel [1965], this suggests an average electron energy of about 50 eV. The data of Fite and Brackmann [1959] for electron impact ionization cross sections at 50 eV for atomic and molecular oxygen yield a value of $K = 0.63$ and consequently a value of $\rho(O)/\rho(O_2) = 1.12$. If the relative number densities from 1965 CIRA-5 (1200 hr) were used and if none of the atomic oxygen had recombined within the gauge, this implies that our estimate of the density would have to be increased by 10% at 400 km, 5.5% at 250 km, and 2% at 160 km.

F. RESULTS

The atmospheric densities derived for revs 21, 25, and 29 over the altitude range from 158 to 420 km are presented in Fig. 8. These revs occurred during a period of moderate solar and magnetic activity. The densities show patchy localized variations and a marked latitude dependence in that the densities measured before perigee (mainly in the northern hemisphere) were higher at a

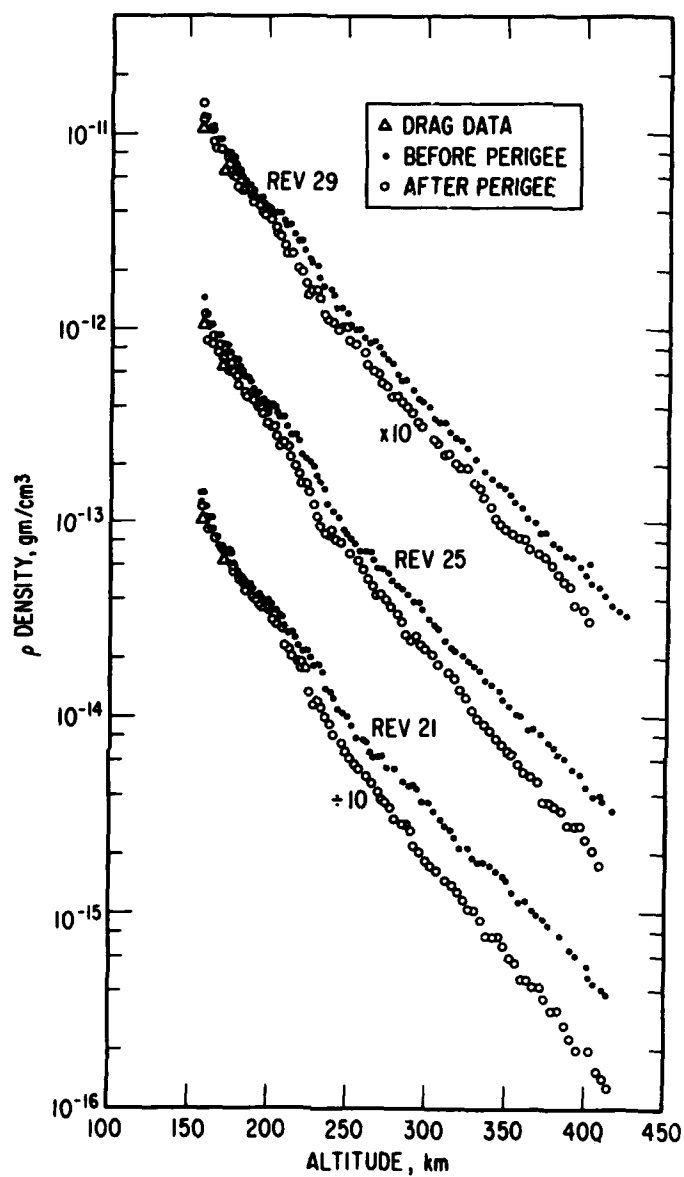


Figure 8. Density vs altitude inferred from pressure measurements during revs 21, 25, and 29 (13 July 1968)

given altitude than those measured after perigee (in the southern hemisphere). Since the measurements were made near summer solstice, the higher northern-hemisphere densities could be ascribed to a density bulge at the subsolar latitude; this explanation will be examined in more detail subsequently.

The statistical and systematic errors in the data were estimated as follows: Above 200 km, the statistical error was predominantly due to the $\pm 6\%$ telemetry bit quantization. Below 200 km, the gauge electrometer output exceeded the telemetry voltage range in the ram, and it was necessary to reduce the data by measuring pressures off ram and inferring a maximum pressure in ram using the $f(s)$ function [see, e. g., Spencer, et al., 1959]. Thus, the statistical error was increased to $\pm 20\%$ to account for the time jitter in the location of the ram position. The total systematic error at perigee was estimated to be between -18 and $+20\%$ (calibration, $\pm 12\%$; uncertainty in M , $\pm 2\%$; aspect, $\pm 1\%$; assumption that $S(O_2) = S(N_2)$, $\pm 3\%$; O vs O_2 , $+2\%$). No attempt has been made to evaluate the possible effects on outgassing of chemisorption and adsorption.

The density profiles for seven revs occurring between revs 21 and 45 were averaged together and are shown in Fig. 9. Over the 2-day period (13-14 July 1968) during which most of the data were obtained, the local time and the daily indices of solar and geomagnetic activity were essentially constant ($LT = 1130$ hr, $F_{10.7} = 156$, and $A_P = 22$).

For comparison, densities from the 1965 CIRA-5 (1200 hr) and the Jacchia [1965] model atmospheres are also presented in Fig. 9. (In calculating density with the 1965 Jacchia model, we have used the recent revisions to the semiannual dependence [Jacchia, et al., 1969], the geomagnetic dependence [Jacchia, et al., 1967], and the bulge parameters [Jacchia and Slowey, 1968].) Both models are based on satellite drag observations and take empirical account of short- and long-term effects of solar activity, geomagnetic activity, and diurnal and semiannual variations. Below 175 km, the CIRA model shows good agreement with the measured density values. At higher altitudes, as expected, the model does not show the observed north-south density difference since it takes no account of the latitude dependence of the subsolar bulge. The 1965

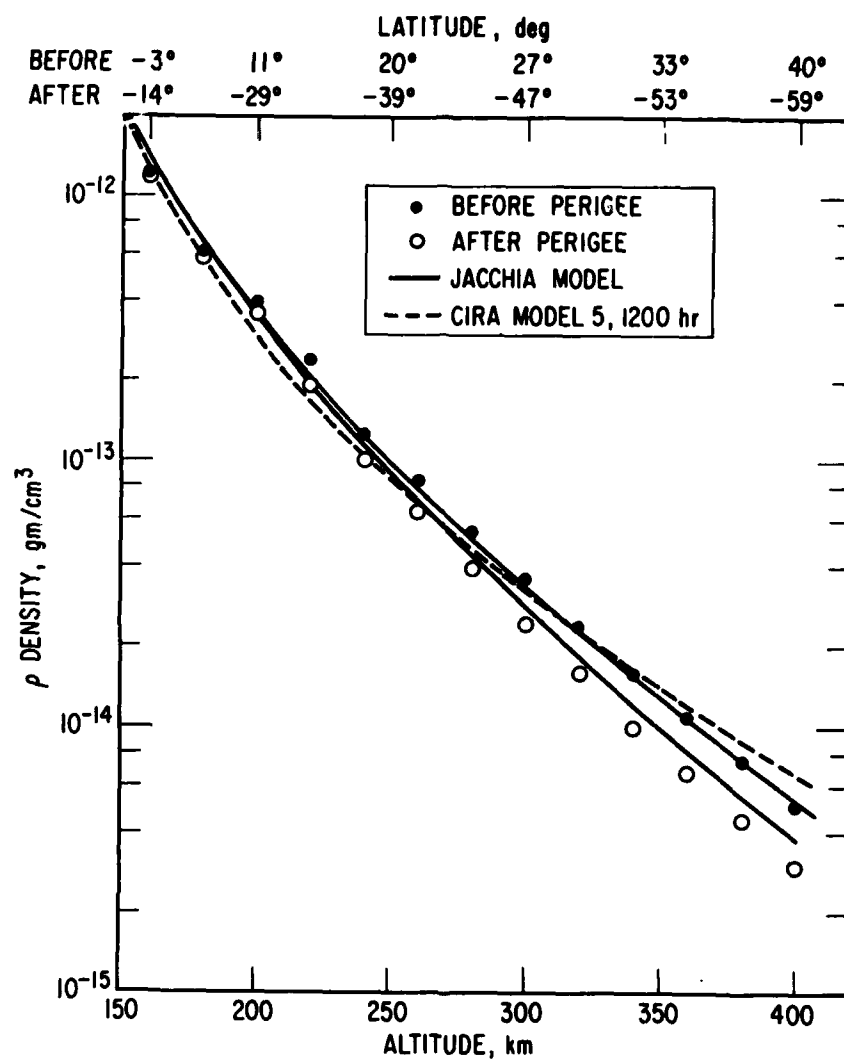


Figure 9. Average density for seven revs over the period 13-15 July 1968, at 1130 hr local time

Jacchia model includes a symmetric density bulge centered at the subsolar latitude at 1400-hr local time, which leads to the latitude dependence shown in Fig. 9. Comparison of data and model suggests that the north-south difference in our measured densities is due mainly to the density bulge, and one might infer that at the highest altitudes (and latitudes) the north-south difference is even more pronounced than indicated by the Jacchia model. However, it should be noted from Fig. 7 that above 350 km the wake pressure after perigee was about 20% of the ram pressure. If, as Moe and Moe [1967] contend, the wake pressure overestimates the gauge outgassing pressure in the ram, then the southern-hemisphere high-altitude densities deduced from our data could be greater, resulting in better agreement with the Jacchia model.

The data in Fig. 9 also show that below 200 km the average measured scale height is greater than that predicted by either model, an observation that has also been made by King-Hele and Hingston [1967].

During the two days of our measurements, a moderate magnetic disturbance occurred; the response of the atmospheric density to this disturbance is illustrated in Fig. 10. Densities from the Jacchia model are plotted in this figure for comparison (the 3-hr K_p values with a 6-hr delay were used in the computation). Several observations can be made. (1) At latitudes below about 40° , the measured density enhancement does correlate with K_p and with approximately the same lag and amplitude inferred from the model. At higher latitudes (which were available to us only in the southern hemisphere) the magnitude of the enhancement decreased markedly with increasing latitude, in contrast to the predictions of the model (as revised by Jacchia, et al. [1967]) that show greater enhancements at high latitudes. It now becomes apparent that the disparity between the average gauge data and the model (Fig. 9) at high southern latitudes was mainly a consequence of the weak response at these latitudes to the geomagnetic disturbance. (2) The duration of the density enhancement was several hours longer than the duration of the geomagnetic disturbance (this effect was noticed by Jacchia and Slowey [1963] but was thought to be a consequence of the inadequate time resolution in the drag data and hence was not included in the model). (3) The measured densities for rev 21 do not agree with the model, a discrepancy that is not understood.

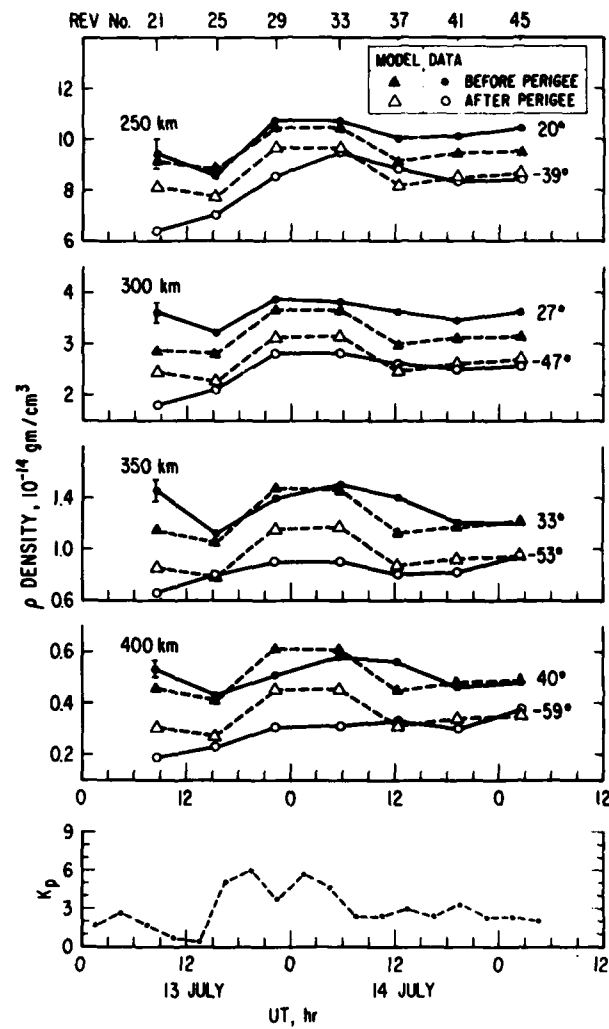


Figure 10. Density at several altitudes vs time

IV. DRAG MEASUREMENT

Radar tracking data in the form of range, azimuth, and elevation, obtained from six passes with an average duration of 5.6 min, were used to define the orbit of the satellite from revs 18 to 34, a period of 1.3 days. The orbit was determined by numerical integration of the equations of motion, by means of Cowell's formulation. The equations of motion included aerodynamic drag, luni-solar attractions, and an 8th-degree, 8th-order geopotential model. The drag term incorporated the L-density [1961] model atmosphere, a drag coefficient C_D of 2.2 (OV1-15 was at all times in the free molecular flow regime), and the attitude and geometry of the satellite. Differences between computed and observed quantities (the radar data) were used for differential correction of seven parameters, the six components of position and velocity at a reference time, and a scaling factor in the drag term. The integration-differential correction process was repeated iteratively until the differences between computed and observed quantities were minimized in the least squares sense. The determination of the drag term scaling factor was equivalent to finding the best average value of the density near perigee corresponding to the data-fitting interval. The average perigee density was 1.04×10^{-12} gm/cm³. However, as pointed out by King-Hele [1966], one should evaluate the density at half a scale height above perigee in order to minimize the effect of using a density model with what may be an incorrect scale height. Evaluated at half a scale height above perigee, the density was 6.3×10^{-13} gm/cm³ at 172 km, which is 14% lower than 7.3×10^{-13} gm/cm³, the average of the gauge measurements for revs 21, 25, and 29. Since the statistical error in this average gauge value was $\pm 12\%$, the densities inferred from drag and gauge are essentially in agreement. The drag-determined density is plotted in Fig. 8 at perigee and half a scale height above perigee.

The statistical error in the drag-determined density due to the uncertainty in perigee height was negligible since the orbit was accurately determined. The effects of electrical drag, solar radiation pressure, and an

increasing drag coefficient in the region of apogee were also negligibly small. The greatest uncertainties lay in the assumed value of C_D of 2.2, and the average presentation area, which was taken to be 0.66 m^2 . Cook [1965] has suggested that a C_D of 2.2 may be too low, by as much as 15%, although he considers the evidence to be insufficient at this time to warrant a change in the currently used value. The 5-deg uncertainty in the direction of the satellite spin vector could increase the presentation area by about 1%. Thus, when the two errors are combined, the drag-deduced density could possibly be too high, by 16%. However, if one is to compare our density value with the results of other drag measurements, the 15% uncertainty in C_D should not be considered, since most analyses use the value 2.2.

V. CONCLUSIONS

The cold-cathode magnetron pressure gauge on the satellite OV1-15 has measured in situ pressures from which atmospheric densities have been inferred for altitudes between 158 and 420 km, at 1130 hr local time. The average of seven density profiles measured over the period 13-15 July 1968 showed that below 200 km the densities were the same in the northern and southern hemispheres, but above 200 km the densities in the northern hemisphere were greater than those at the same altitudes (but different latitudes) in the southern hemisphere. This north-south difference is in fairly good agreement with that predicted by the Jacchia [1965] model (appropriate to extant conditions), which includes a symmetric density bulge centered at the subsolar latitude at 1400-hr local time.

A rev-by-rev comparison of measured and model densities during a moderate geomagnetic disturbance (maximum $K_p = 6$) shows that, at latitudes below about 40° , the magnitude and lag (6 hr) of the atmospheric density enhancement is adequately described by Jacchia's empirical formulas, except that the duration of the enhancement was several hours longer than the duration of the geomagnetic disturbance. At latitudes above 40° (which were available to us only in the southern hemisphere) the magnitude of the density enhancement decreased markedly with increasing latitude, in contrast to the predictions of the model (as revised by Jacchia, et al. [1967]) that show greater enhancements at high latitudes.

The gauge-determined density at half a scale height above perigee was the same, within the estimated errors, as the density determined from an analysis of the decay of the satellite's orbit. The Explorer 17 data reported by Newton, et al. [1965] showed gauge density to be about one-half of that deduced from drag, a discrepancy that does not exist in the OV1-15 results. The principal differences between the two experiments were the satellite spin rates (Explorer 17 was 10 times faster), the gauge housing materials,

(Explorer 17 used glass, and OV1-15 used stainless steel), and a different ambient atmosphere at perigee (Explorer 17 was in the dominantly O regime whereas OV1-15 was in the dominantly N₂ regime).

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13. ABSTRACT <p>A cold-cathode magnetron pressure gauge and a C-band radar beacon were part of the complement of experiments aboard the polar-orbiting atmospheric research satellite OV1-15 (1968-059A). Over the period 13-15 July 1968, when the perigee of the satellite was near the equator at about local noon, the atmospheric density profiles were repeatedly measured down to 158 km. The profiles agreed in the northern and southern hemispheres below 200 km, but above 200 km the northern profile was greater than the southern, in approximate agreement with the Jacchia model that includes a symmetric density bulge at the subsolar latitude at 1400 hr local time.</p> <p>During a moderate magnetic disturbance, the atmospheric density at latitudes below about 40° increased with an amplitude and lag that are adequately described by the Jacchia model, except that the duration of the density enhancement was several hours longer than the duration of the geomagnetic disturbance. At latitudes above 40° (which were available to us only in the southern hemisphere), the density enhancement decreased markedly with increasing latitude, an occurrence not predicted by the model.</p> <p>The drag-determined density near perigee was the same, within the estimated errors, as that determined from the gauge measurement, in contrast to the factor-of-two discrepancy found in a similar comparison of data from the satellite Explorer 17.</p>		

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